SEARCHES IN PHOTON AND JET STATES

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We present recent results from the Collider Detector at Fermilab (CDF) and DØ experiments using data from proton-antiproton collisions with $\sqrt{s} = 1.96\,\mathrm{TeV}$ at Run II of the Fermilab Tevatron. New physics may appear in events with high transverse momentum objects, including photons and quark or gluon jets. The results described here are of signature-based searches and model-based searches probing supersymmetry, leptoquarks, 4^{th} generation quarks, and large extra dimensions.

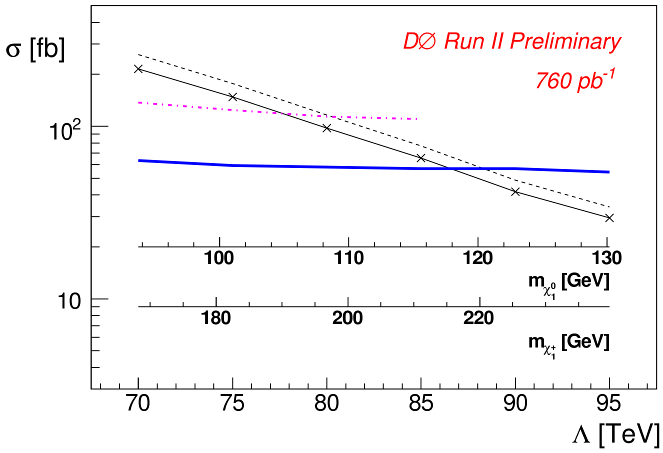
1 Signature Based Searches

1.1 Searches in $\gamma\gamma$ + $\{e,\ \mu,\ \gamma,\ \not\!\!E_T\}$

The signature-based search for two photons plus an additional photon, electron, muon, or missing transverse energy ($\not\!\!E_T$) at CDF in Run II [1] is motivated by an anomalous Run I event [2] containing $ee\gamma\gamma\not\!\!E_T$, and the fact that new physics may appear in events with multiple high transverse momentum (p_T) particles. This signature may occur in numerous scenarios beyond the standard model (SM): pair-production of supersymmetry (SUSY) particles that yield multiple photons as they decay to lower mass states (for example, through $\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0$); pair-production and radiative decays of other excited states ($X^*X^* \to \gamma X\gamma X$); b' quark pair production and decay; fermiphobic Higgs decays yielding photons; and gauge-mediated supersymmetry breaking (GMSB) scenarios. Using data corresponding to an integrated luminosity of $1.0 - 1.2\,\mathrm{fb}^{-1}$, the number of observed events $(4, 1, 3, 0)$ in each of the four final states $(\gamma\gamma\gamma, \gamma\gamma\not\!\!E_T, \gamma\gamma e, \gamma\gamma\mu)$ is consistent with the expected number of events due to SM processes $(2.2, 0.24, 6.8, 0.7)$.

Table 1: Number of expected and observed events for the $\ell\gamma + \{\ell, \gamma, \not\!\!E_T\}$ search, and the dominate SM processes.

	$ee\gamma$	$\mu\mu\gamma$	$e\mu\gamma + X$	$e\gamma\gamma$	$\mu\gamma\gamma$	$e\gamma\not\!\!E_T$	$\mu\gamma\not\!\!E_T$
Expected (SM)	39 ± 5	26 ± 3	1.0 ± 0.3	0.5 ± 0.1	0.1 ± 0.1	95 ± 8	56 ± 7
Dominant Source	$Z\gamma$	$Z\gamma$	$Z\gamma$	e fakes γ	jet fakes γ	$W\gamma$	$W\gamma$
Observed	53	21	0	0	0	96	67



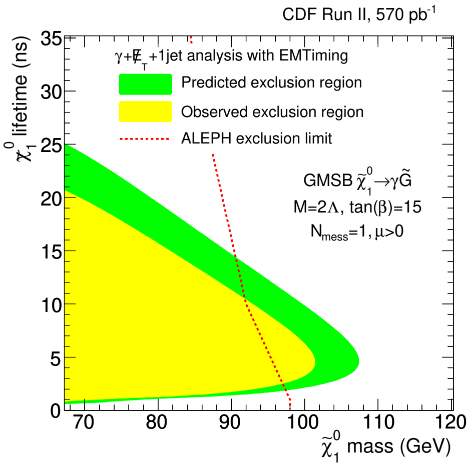


Figure 1: (left) Cross section limit for GMSB scenario as a function of SUSY breaking scale, assuming prompt photons. (right) Exclusion regions for a GMSB scenario with delayed photons.

1.2 Searches in $\ell\gamma + \{\ell, \gamma, \not\!\!E_T\}$

An additional signature-based analysis at CDF searches for events containing an electron or muon ($\ell = e$ or μ) with $p_T > 25\,\mathrm{GeV}/c$, a photon with $E_T > 25\,\mathrm{GeV}$, and an additional object, which can be an electron, muon, photon, or $\not\!\!E_T$ [3]. This search, which uses $929\,\mathrm{pb}^{-1}$, is motivated by a 2.7σ excess found in Run I in the $\ell\gamma\not\!\!E_T$ final state [4]. In that search, 16 events were observed compared to an expectation of 7.6 ± 0.7 events due to SM sources. The current search uses the same event selection criteria, but about 10 times the amount of data, and observes 163 $\ell\gamma\not\!\!E_T$ events compared to a SM expectation of 150.6 ± 13.0 events. Table 1 shows the expected and observed number of events for the individual channels, as well as the dominant SM process which yields each signature. In all cases, the observations are consistent with the SM.

2 Supersymmetry

2.1 Gauge Mediated Supersymmetry Breaking in $\gamma\gamma\not\!\!E_T$

The spectrum of particles predicted by SUSY theory, which is a popular SM extension, depends upon the mechanism by which SUSY is broken. One possibility is the GMSB scenario, where $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\tilde{G}\gamma\tilde{G}$, yielding a signature of two photons and $\not\!\!E_T$ from the gravitinos ($\tilde{G}$). A search using $760\,\mathrm{pb}^{-1}$ at DØ expects 2.1 ± 0.7 events from SM sources and observes 4 events [5]. Assuming short neutralino lifetime, so that the photons are produced promptly, 95% C.L. limits are set at $m(\tilde{\chi}_1^0) > 120\,\mathrm{GeV}/c^2$ and $m(\tilde{\chi}_1^\pm) > 220\,\mathrm{GeV}/c^2$. Figure 1(left) shows the cross section limit as a function of the SUSY breaking scale parameter Λ. The other parameters of the model are fixed at the so-called SPS8 values [6].

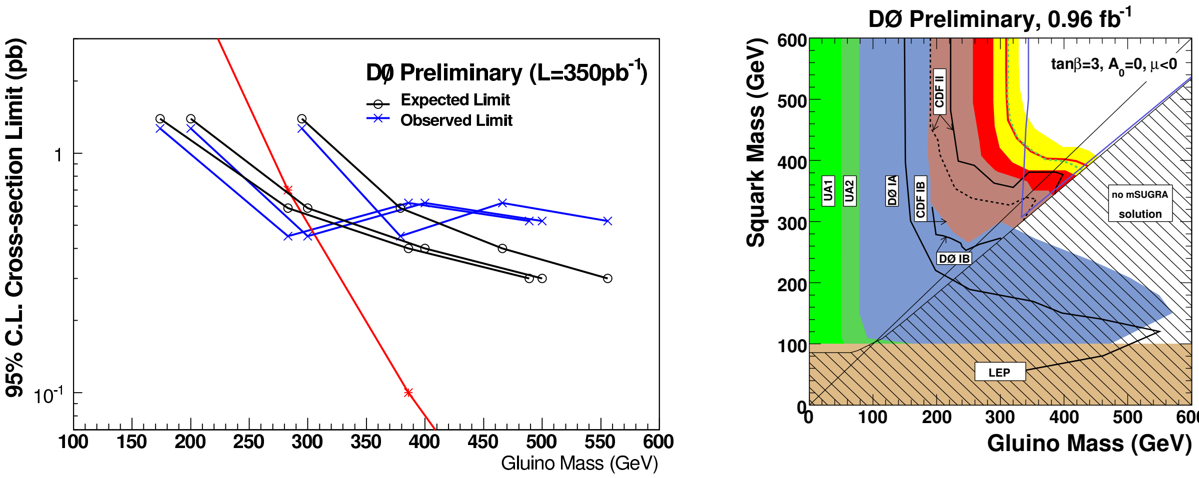


Figure 2: (left) Expected and observed gluino production cross section as a function of gluino mass for stopped gluino scenarios with $m(\tilde{\chi}_1^0) = 50, 90, 200\,\mathrm{GeV}/c^2$ (pairs of black and blue lines, left to right) and the theoretical cross section (red line). (right) Excluded regions for the squark and gluino search, showing the newly excluded region in red and associated theoretical uncertainty in yellow.

2.2 Search for Delayed Photons

The detection of photons produced after a delay with respect to the primary interaction may indicate the presence of new phenomena. These photons may stem from decays of heavy, neutral, long-lived particles, such as in the GMSB scenario, with $\tilde{\chi}_1^0 \to \gamma\tilde{G}$. Using $570\,\mathrm{pb}^{-1}$, CDF searches for delayed photons in the $\gamma\not{E}_T$+jet channel [7]. The measurement uses a new timing system in the electromagnetic calorimeter. The signal selection requires the photon time of arrival to be $2 < t < 10\,\mathrm{ns}$, reducing backgrounds from beam halo, cosmic rays, and prompt photons. We expect 1.3 ± 0.7 SM events and observe 2 events. Figure 1(right) shows the resulting exclusion regions in the plane of neutralino lifetime and mass, assuming SPS8 parameters as in section 2.1.

2.3 Search for Stopped Gluinos

In split-SUSY [8], the SUSY scalers are heavy (possibly of the grand unification scale) compared to the SUSY fermions. Split-SUSY models predict long-lived gluinos ($\tilde{g}$), which could have time to hadronize, lose momentum through ionization, and come to rest in the calorimeter. Using $350\,\mathrm{pb}^{-1}$, DØ searches for $\tilde{g} \to g\tilde{\chi}_1^0$ in the jet+$\not{E}_T$ channel [9], where the gluon yields a jet and the unobserved $\tilde{\chi}_1^0$ results in $\not{E}_T$. The selection requires one jet with $E > 90\,\mathrm{GeV}$, in an otherwise empty event. Background from cosmic ray muons is reduced by requiring wide jet showers in the calorimeter with no associated muon, since jets are wide for the hypothetical signal but narrow for muons. Additional beam-induced background is successfully removed. Cross section limits are set as a function of jet energy and translated into gluino mass limits. The search sets a limit of $m(\tilde{g}) >\sim 270\,\mathrm{GeV}/c^2$ for an example with $m(\tilde{\chi}_1^0) = 50\,\mathrm{GeV}/c^2$. Figure 2(left) shows cross section limits as functions of gluino mass.

2.4 Search for Squarks and Gluinos

In the minimal supergravity (mSUGRA) formulation of SUSY, pair produced squarks and gluinos ($\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$) can decay through $\tilde{q} \to q\tilde{\chi}_1^0$ and $\tilde{g} \to q\tilde{q}\tilde{\chi}_1^0$ to yield signatures with 2, 3, or 4 jets from the quarks and $\not{E}_T$ from the neutralinos. A search at DØ combines these three channels [10], categorized by the number of jets, to set 95% C.L. limits on the squark and gluino

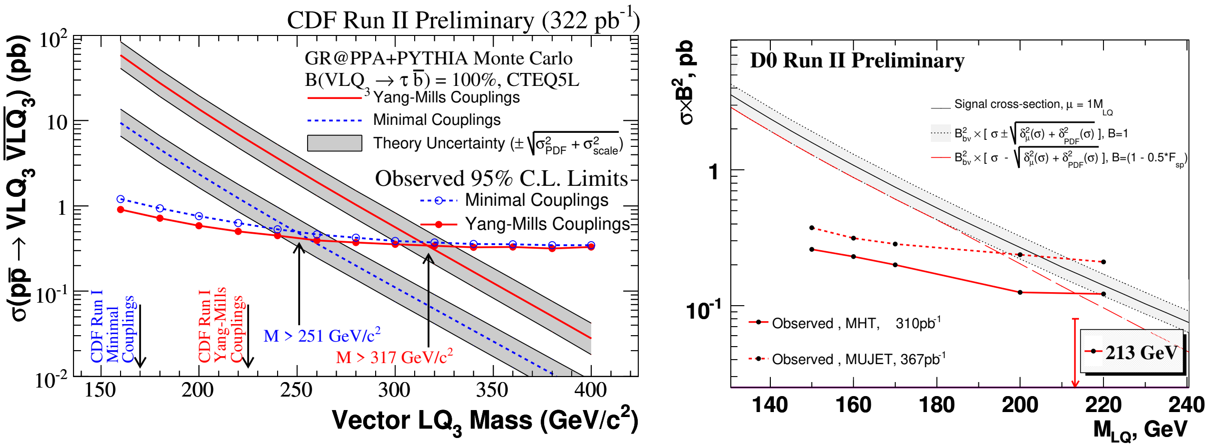


Figure 3: (left) Cross section versus mass for 3rd generation vector leptoquarks, showing observed limits and theoretical predictions for two coupling scenarios. (right) Limits for 3rd generation scalar leptoquarks as a function of *SLQ*3 mass. The results quoted in the text are for the observed limit called MHT in this figure.

masses of $m(\tilde{q}) > 375\,\mathrm{GeV}/c^2$ and $m(\tilde{g}) > 290\,\mathrm{GeV}/c^2$, using $960\,\mathrm{pb}^{-1}$. Figure 2(right) shows the excluded regions in the squark–gluino mass plane.

3 Leptoquarks

3.1 3rd Generation Vector Leptoquarks

Leptoquarks may provide a link between the families of quarks and leptons at higher mass scales. They appear in a variety of beyond the SM theories. At the Fermilab Tevatron, leptoquarks could be predominately pair produced through quark anti-quark annihilation. Using $322\,\mathrm{pb}^{-1}$ of CDF data, we consider the case of 3rd generation vector leptoquarks ($VLQ3$), where each decays exclusively to τb [11]. The decay products, $\tau b \tau \bar{b}$, are reconstructed as two jets from the b quarks, one leptonically decaying tau, and one hadronically decaying tau. At 95% C.L., we set a limit of $m(VLQ3) > 317\,\mathrm{GeV}/c^2$ for a model with Yang-Mills type couplings [12]. Figure 3(left) shows the cross section limits as a function of $VLQ3$ mass for two models.

3.2 3rd Generation Scalar Leptoquarks

Complementary to the search mentioned above, leptoquarks may also appear as spin=0 objects. A search at DØ assumes 3rd generation scalar leptoquarks ($SLQ3$) are pair produced and decay primarily via $SLQ3 \to \nu b$, but also allows for $SLQ3 \to \tau t$ [13]. The considered decay products, $\nu b \bar{\nu} \bar{b}$, yield a signature of 2 b-jets and $\not\!\!E_T$ from the neutrinos. Based on $310\,\mathrm{pb}^{-1}$, the 95% C.L. limit is $m(SLQ3) > 213\,\mathrm{GeV}/c^2$. If $SLQ3 \to \tau t$ is explicitly forbidden, the limit is $m(SLQ3) > 219\,\mathrm{GeV}/c^2$. Figure 3(right) shows these results.

3.3 2nd Generation Scalar Leptoquarks

As with the other leptoquark searches, to avoid producing flavor changing neutral currents, it is common to assume that generation number is conserved in the decays. Therefore a search for 2nd generation scalar leptoquarks ($SLQ2$) at DØ assumes the decays contain muons or muon neutrinos, and second generation quarks ($q = s$ or c) [14]. We consider the branching ratio $\beta \equiv \mathcal{B}(SLQ2 \to \mu q) = 0.5$, so that pair production and decay leads to a final state of $\mu q \nu q$. The signature is one muon, 2 jets, and $\not\!\!E_T$. In $1\,\mathrm{fb}^{-1}$, 6.1 ± 1.1 events are expected from SM

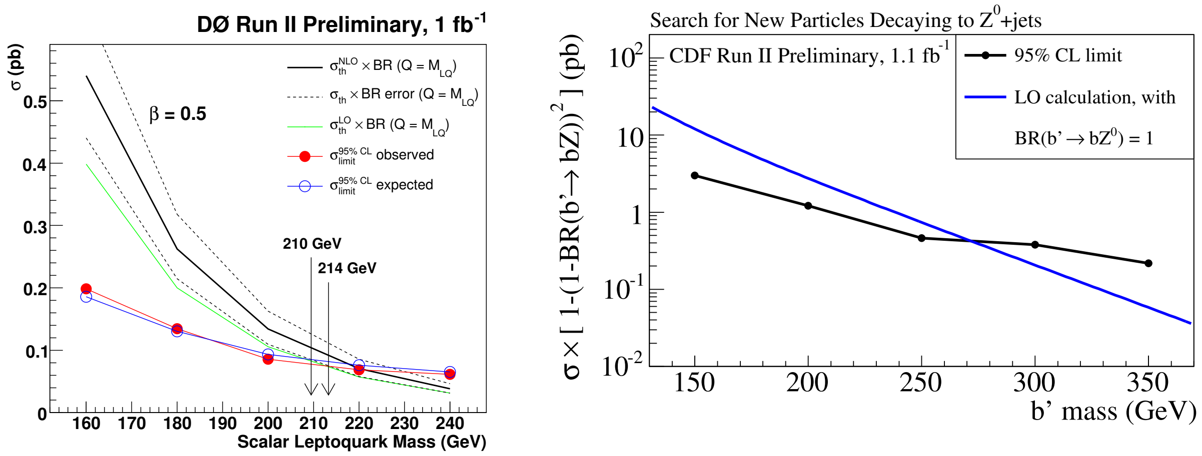


Figure 4: (left) Cross section limit for 2$^{\text{nd}}$ generation scalar leptoquarks as a function of mass. (right) Observed limit and theoretical prediction for a 4$^{\text{th}}$ generation b' model, in the search for new particles that couple with Z bosons.

backgrounds, while 6 events are observed. The 95% C.L. limit is $m(SLQ2) > 214\,\mathrm{GeV}/c^2$, as shown in figure 4(left).

4 Search for b'

A search for b' 4$^{\text{th}}$ generation quarks is carried out at CDF, as a specific case to quantify the acceptance, in a general search for new particles that couple to Z bosons and jets [15]. The production and decay chain considered in the analysis is $q\bar{q} \to g \to b'\bar{b}' \to bZ\bar{b}Z$, with one Z decaying through $Z \to \ell\ell$ and the other decaying through $Z \to q\bar{q}$. The leptonically decaying Z is reconstructed in the $Z \to ee$ and $Z \to \mu\mu$ channels, with lepton $p_T > 20\,\mathrm{GeV}/c$, and we require ≥ 3 jets with $E_T > 30\,\mathrm{GeV}$. The leading background, from SM Z+jet events, is estimated by using events with < 3 jets to predict the contribution for events with ≥ 3 jets. Using $1.1\,\mathrm{fb}^{-1}$, the 95% C.L. limit is $m(b') > 270\,\mathrm{GeV}/c^2$, as indicated by the intersection of the observed and theoretical curves in figure 4.

5 Large Extra Dimensions

Large extra dimensions have been proposed [16] as a potential solution to the hierarchy problem between the weak and gravitational forces. In these models, only gravitons (G) can propagate in the n extra dimensions of the $4+n$ dimensional bulk of space-time. The Planck scale (M_{Planck}) is so large, and the strength of gravity so small, due to the large extent (R) of the extra spacial dimensions. To address the hierarchy problem, the new effective Planck scale (M_D) is related to the other quantities through $M^2_{\text{Planck}} \sim R^n M_D^{2+n}$. The gravitons can be directly produced via $qq \to gG$, $qg \to qG$, or $gg \to gG$, in all cases yielding an energetic jet from the quark or gluon, and $\not{E}_T$ from the graviton. The measurement at CDF, using $1.1\,\mathrm{fb}^{-1}$, observes 779 events while expecting 819 ± 17 events from SM sources. This is an update, using the same selection but more data, of the previously published results [17]. These new results are used to place lower limits on M_D and upper limits on R. The lower limits on M_D are given in figure 5, with corresponding upper limits on R of $R < 0.27\,\mathrm{mm}$, $R < 3.1 \times 10^{-6}\,\mathrm{mm}$, $R < 9.9 \times 10^{-9}\,\mathrm{mm}$, $R < 3.2 \times 10^{-10}\,\mathrm{mm}$, and $R < 3.1 \times 10^{-11}\,\mathrm{mm}$ for $n = 2, 3, 4, 5$, and 6.

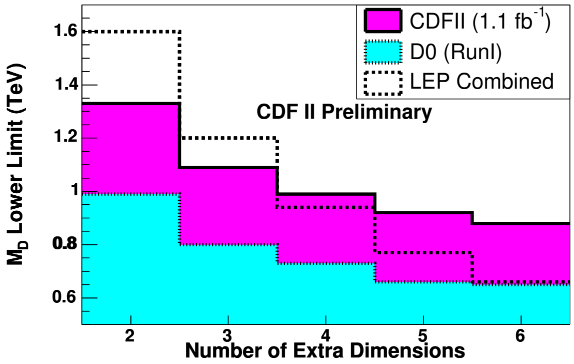


Figure 5: Lower limits on the effective Planck scale as a function of the number of large extra dimensions.

6 Conclusions

Various searches for new physics at DØ and CDF using photons and jets are constraining specific models, while signature based searches are looking for deviations from the SM. Discoveries may be just around the corner, as additional analyses and larger data sets are considered.

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